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Gamma-ray spectrometry for confined fast ion studies in D3He plasma experiments on JET

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Gamma-ray spectrometry of the plasma [1] is one of the tools giving information on the heating efficiency. The source of gamma-ray is nuclear reactions between energetic confined ions and plasma impurities, i.e. Be and bulk plasma ions. Gamma-ray diagnostics allow monitoring the energy distributions of the fusion products, ions accelerated during ICRF heating and plasma fuel ions and provide an effective optimization of high-performance discharge scenarios with additional plasma heating (NBI and ICRF).
In the recent JET experiments at 3.7T/2.5MA, D-NBI ions were accelerated to MeV energies using the 3-ion ICRH scheme D–(D NBI)–3He [2] in D3He mixed plasmas. There are three essential components in the plasma: thermal deuterium, 20-25% of thermal 3He and D-NBI ions that effectively adsorb ICRF power at the mode conversion layer in the plasma core.
In the experiments, two large volume LaBr3(Ce) Ø3"x6"spectrometers [3] with vertical and tangential lines-of-sight (LoS) were used. They allow measuring high-resolution and time-resolve spectra up to ~30 MeV during plasma discharge. In some high performance discharges the vertical LaBr3(Ce) detector was replaced with a high-resolution HpGe spectrometer [4] for measurements of the Doppler broadening of gamma-lines in recorded spectra. In addition to these highly efficient spectrometers, the gamma-ray camera, consisting of 19 compact LaBr3(Ce) detectors [5] with 10 horizontal and 9 vertical LoS, was used for obtaining 2D gamma-ray emission profiles measurements. In the recorded during plasma discharges spectra of both vertical and tangential spectrometers, gamma-ray lines corresponding to transitions in the nuclei 10Be and 10B excited in the 9Be(D,pγ)10Be and 9Be(D,nγ)10B nuclear reactions were identified. The line-integrated energy distribution function of the fast D-ions was reconstructed with a specially developed gamma-ray spectrum analysis code DeGaSum [6]. This code allows reconstructing the fast D-ion energy distribution using the measured gamma-ray line intensities together with the known excitation functions of the reactions. To obtain intensities of the gamma-rays generated in the plasma discharge, we used the spectrometer response functions calculated for monoenergetic gamma-rays in the energy range 0.5 - 30 MeV. For these calculations both the vertical and tangential spectrometer LoS models were used. An example of the data processing results is presented in figure 1a, where one can see both measured gamma-ray spectrum (black line) and the restored energy distribution of the gamma-rays emitted from plasma (red line). Figure 1b shows the reconstructed energy distribution of the confined D-ions that was obtained using 3.37-MeV gamma-ray line from 9Be(D,pγ)10Be reaction and 2.86- and 3.59-MeV lines from 9Be(D,nγ)10B reaction. In the Maxwellian approximation, the effective temperature of fast D-ions is ~600 keV in the plasma discharge #94701.

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In these experiments, due to a high concentration of 3He in the plasma and strong population of the energetic D-ions, the 3.6-MeV alpha-particles were generated in the fusion reaction 3He(D,p)4He. The source of the fusion-born alpha-particles (rate and spatial profile) could be measured with 3He(D,γ)5Li reaction, which is a weak branch of the main fusion reaction; the 3He(D,γ0)5Li/3He(D,p)4He branch ratio is ~3·10^(-5). This reaction gives rise gamma-rays with energy ~16.7 MeV. It was identified in the recorded spectra. Measuring intensity of the 16.7- MeV gammas, the fusion born alpha-particle rate production was estimated in discharges, i.e. ~4.2·10^13 m-3·s-1 for the #94701 discharge. The spatial distribution of the confined alpha-particles was obtained by measurements of the 4.44-MeV gamma-rays from the 9Be(α,nγ)12C reaction [2]. This line is strong and clearly seen in the recorded spectra (figure 1a). These gamma-ray measurements have provided a comprehensive test of the diagnostics and analysis methods that are required for alpha-particle studies in forthcoming DT-experiments.
In fusion reactors, the source of DT alpha-particles and their behaviour in the plasma should be under control to provide the high fusion performance. The presented paper demonstrates the capability of the gamma-ray spectrometry for such control. The inferred deuterium energy distributions, as well as the assessment of the D3He fusion rate, have allowed optimizing the ICRF heating scenario.
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